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Near-field self-interference suppression with subscriber beamforming in full-duplex communications

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ABSTRACT

With a wide range of spatial domain self-interference (SI) suppression techniques in full-duplex (FD) systems, the available literatures focus on verifying the feasibility of the types of technologies used in the experiments. The current literatures overlook the principle that the local receive antennas are always in the near-field of the local transmit antennas when the antennas are separate and omnidirectional. If near-field assumption of the SI channels is considered, more degrees of freedom are achieved. This may reduce the impact on the remote users while adopting spatial domain SI suppression. Thus, a minimization of the near-field spatial SI with the remote user beamforming is stated. First, it is reformulated and solved by least square (LS) method. Second, the problem can be relaxed by l_1 norm and solved by linear programming. The simulation results are used to analyze the impact of the near-field spatial SI suppression on the remote user. The SI suppression is feasible even when the local receive antenna in the near-field and the users in the far-field are in the same direction.

1. Introduction

Full-duplex (FD) wireless communication systems, which transmit and receive the signals simultaneously in the same frequency channel, seek to raise spectral efficiency. As a new communication scheme, it has been extensively used in the secure communication systems [1], distributed antenna networks [2], and non-orthogonal multiple access systems [3]. The FD is in contrast to the half-duplex (HD) operation, where each node receives and transmits using the dual-orthogonal channels, and thus this cannot use spectrum efficiently. The major challenge in achieving FD wireless communication systems is dealing with the strong self-interference (SI) created by the transmitter antennas to its own receiver antennas [4]. Recent studies showed that, using multiple mitigation stages, which can be divided into three types such as antenna domain cancellation, RF domain cancellation, and digital domain cancellation, the SI can be sufficiently attenuated to detect the intended signal [4–16]. The SI mitigation should be conducted before low noise amplifier (LNA) and analog-to-digital converter (ADC) to avoid saturation. Furthermore, the SI cancellation can be done at the baseband. Generally, both of the antenna-based mitigation technique [5] and RF cancellation technique [6,7] are the two main techniques to avoid the receiver chain saturation. This paper mainly focuses on the spatial domain technique.

The spatial SI suppression technologies have been fully studied in the FD relays and communication systems. Riihonen et al. [8] gives an overview of the loopback mitigation of SI in the field of FD relays. The nature propagation is the first choice to guarantee the basic SI isolation. As cited above, the simple antenna selection or singular value decomposition (SVD)-based beam selection can suppress the SI under a certain level. Also, the SI can also be suppressed effectively by null-space projection (NSP). Based on observations [8], the SI cannot be perfectly cancelled by any spatial suppression technologies because of the transmitter noise and imperfect side information used for mitigation. In [9] compact and high isolation antennas are designed and manufactured for the FD multiple input multiple output (MIMO) relay. Zhang et al. [10] presents a comprehensive list of the potential FD techniques where the spatial suppression schemes can be found (see [10] and the references therein).

At the start of the FD research, Choi et al. [11] has proposed an asymmetric antenna placement technique that can efficiently cancel SI. Compared with the single antenna case, the antenna cancelation scheme would lead to a far-field nulling point at the local receive antenna direction. Khojastepour et al. [12] presents an antenna cancellation approach based on a symmetric antenna placement. However, it will generate a power depression area at the center of the symmetric antennas while the remote users'

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power can be seriously attenuated. More experiments and studies are carried out in [13,14]. Also, a time-domain transmit beamforming is also presented [15]. A hardware-based test regarding the time-domain transmit beamforming method shows a 50 dB SI cancellation including the unknown specific nature loss over a 30 MHz bandwidth. The scheme of multiple input multiple output (MIMO) FD communication system is developed in [16] despite this scheme is still in the infancy.

As a whole, the existing literatures have successfully verified the feasibility of the various spatial SI suppression techniques in the experiments. For directional antenna arrays in relay scenario, the FD antenna arrays are designed using the rigorous electromagnetic modeling [9]. However, for the omnidirectional antenna arrays, the available literatures do not clearly identify whether the local receive antennas are present or not in the near-field of the local transmit antennas. In general, the spherical and plane wave models are used in formulating the near-field and far-field scenarios respectively. Fig. 1 illustrates the plane and spherical wave models [17]. The plane wave model assumes that the transmit signal from different antennas is a plane wave, which means the direction-of-arrival (DOA) depicted as $\theta_i, i = 1, 2, 3, \dots$ in Fig. 1 is same for all the transmit antennas in the receive antenna. When the spherical wave model is used, the DOA depicted as $\phi_i, i = 1, 2, 3, \dots$ in Fig. 1 is not the same for the transmit antennas in the receive antenna. Compared to the far-field assumption of the plane wave model, the near-field assumption used in the spherical wave model is noted because the space degrees of freedom of arrival angles are increased. If the local receive antennas are located in the near-field of the local transmit antennas, the spatial SI suppression performance will be improved. Also, another task of the local transmit antennas is providing contents for the remote users. The minimization of the near-field spatial SI under a beamforming gain of the remote users is formulated. The main contributions of this paper could be summarized as follows: (1) with omnidirectional separate local transmit and receive antennas, the problem to suppress the near-field SI while simultaneously maintaining gain towards the far-field users was initially studied; (2) next, we give two approaches, i.e., the least square method and the relaxation linear program to solve the non-convex problem, and then analyze the relaxation linear program approach's stability; (3) finally, we provide the simulation results to highlight that the SI can be suppressed despite the local receive antenna was in the direction of the far-field user.

2. Transceiver architecture

Fig. 2 shows a simple transceiver architecture in FD communication system, where the transmit beamforming unit includes a power splitter, N attenuators, N phasers, and N transmit antennas. To simplify, only one local receive antenna is considered. The transmit beamforming vector can be expressed as

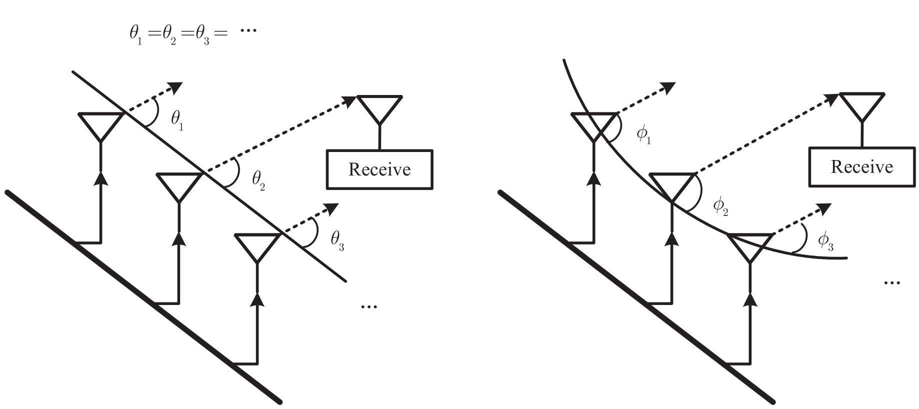
$$\boldsymbol{w} = \left(a_1 e^{j\phi_1}, a_2 e^{j\phi_2}, \dots, a_N e^{j\phi_N}\right)^T, \quad (1)$$

where $a_i, i = 1, 2, \dots, N$ denotes the attenuator value, $\phi_i, i = 1, 2, \dots, N$ denotes the phaser value, and $(\cdot)^T$ denotes matrix transpose.

In this paper, the local transmit antennas have two functions. First, the antennas provide the beamforming gain for the remote users in certain directions. Second, they are used for suppressing the SI in spatial domain before the digital SI cancellation at the baseband. Because of the nonlinearities of the power amplifier (PA), only one PA is adopted and the output of the PA is equally divided and assigned for each antenna by the power splitter. This ensures the suppression of linearity and nonlinearities of SI by transmit beamforming. When used, the adopted radio frequency (RF) beamforming can be expanded to the baseband beamforming such as orthogonal frequency-division multiplexing (OFDM) based beamforming which can be optimized in the frequency domain separately within each channel coherence band. However, transmitter hardware impairments would significantly degrade the performance of the baseband beamforming. Meanwhile, the high transmit signal-to-noise (SNR) is needed for baseband beamforming. The RF beamforming without the specific requirements of the transmit SNR in this paper.

In the FD field, a problem statement that reduces the SI under certain intended signal gain at specific SI channel value and intended channel value has been extensively carried out. However, these studies don't show how the near-field spatial SI suppression can impact the signal receiving of the remote user by using the freedom of the near-field spatial SI channel. In this paper, it is assumed that the local receive antenna is located in the near-field of the local transmit antennas and the latter are linearly and equally distributed. Therefore, the line-of-sight (LOS) SI fading coefficient from the ith transmit antenna to the local receive antenna is calculated according to the formula [17]

$$A_i(\boldsymbol{r}, f) = \frac{1}{\|\boldsymbol{r} - \boldsymbol{r}_i\|} e^{\frac{-j2\pi f \|\boldsymbol{r} - \boldsymbol{r}_i\|}{c}}, \quad (2)$$



(a) Plane wave model (b) Spherical wave model

Fig. 1. Description of (a) the plane wave model and (b) the spherical wave model.

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